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Energy analysis of semi-transparent BIPV in Singapore buildings

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A B S T R A C T

Buildings consume large amounts of energy and semi-transparent building-integrated photovoltaic (BIPV) has the potential to increase their energy efficiency. BIPV windows affect building energy consumption through solar heat gain, daylighting and electricity production. This study examines six commercially available semi-transparent BIPV windows; four single-glazed and two double-glazed. A new index was formulated to evaluate the overall energy performance of semi-transparent BIPV in terms of increase/decrease of cooling energy, artificial lighting energy and generation of electricity. Parametric simulation studies based on different window-to-wall ratios and orientations to obtain annual energy consumption were performed for the case of Singapore. Selected results of semi-transparent BIPVs were also compared against commonly used window types such as single-glazing, doubled-glazing and low-emissivity windows. The results showed the potential to adopt semi-transparent BIPV across all orientations in tropical countries such as Singapore. A variety of design strategies optimizing the window-wall-ratio for various orientations will be necessary to achieve the highest electricity benefit with different modules.

1. Introduction

According to the International Energy Agency (IEA), the world energy consumption increased by nearly 40% from 1990 to 2007 and will continue to increase by another 8–10% every 5 years until 2035, which can be partially attributed to rapid urbanization and development [1]. Globally, buildings represent close to 40% of primary energy usage and if energy consumed in manufacturing steel, cement, aluminium and glass used in building construction is included, this grows to more than 50% [2]. One way to improve a building's energy balance is to use energy efficient materials to improve the performance of building facades. In modern buildings, windows play an important role in energy performance with respect to heating/cooling loads and artificial lighting requirements. The relationship between window design and building energy performance has been extensively researched [3–10].

Building-integrated photovoltaic (BIPV) windows have been proposed by many as an innovative and emerging glazing technology for use in the construction industry [11–13]. When fully integrated through proper design, BIPV windows have the capability to displace conventional building façade materials while retaining their traditional functional roles and also providing the additional benefit of electricity generation. The effects of integrating photovoltaic glazing systems however have to be analyzed from three main aspects: optical and thermal performance, along with electricity production. Fig. 1 illustrates the implications of semi-transparent BIPV adoption for buildings in tropical climates where heat gain and cooling loads are critical elements of a building's energy performance.

However to date, research on the multi-functional effect of semi-transparent BIPV on the total energy balance is limited. Current research includes studies which have considered the design and use of semi-transparent BIPV windows through experimental and modelling approaches. With respect to total building energy consumption, Miyazaki et al. [14] and Li et al. [15] reported research findings on semi-transparent BIPV applied on buildings' facades. Miyazaki et al. undertook a simulation study to find the optimum transmittance of semi-transparent solar modules and to estimate possible energy savings of office buildings by considering the heating and cooling loads, daylighting and electricity production. A double-glazed semi-transparent amorphous silicon solar module was adopted for the study which was performed under the climatic conditions of Tokyo, Japan. They reported that the minimum electricity consumption in the building was achieved with 40% solar cell transmittance and 50% window-to-wall ratio (WWR) and the

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Nomenclature

BOS	balance of system
COP	coefficient of performance
SHGC	solar heat gain coefficient
VLT	visible light transmittance [%]
WWR	window-to-wall ratio [%]
U-value	thermal transmittance [W/(m^2 K)]

energy savings achieved for the total cooling load was 54%. Li et al. studied the thermal, visual and electrical properties along with the financial aspects of a semi-transparent photovoltaic facade. Physical field measurements were conducted to determine the module's critical parameters before a generic high-rise office building was modelled as a case study using Hong Kong's recorded weather data. It concluded that the electricity benefit amounted to 12% of the total building electricity expenditure annually. With that result, the simple payback period was estimated to be approximately 15 years.

The impacts of integrating semi-transparent PV, in terms of electricity production and reduction of cooling load in the Middle East [16,17], and sub-tropical [12] climates have been explored and discussed previously. Bahaj et al. [16] investigated the implications of emerging glazing technologies including semi-transparent thin-film photovoltaic modules, for energy control of highly glazed buildings in Middle Eastern climates, where it is largely tropical and cooling energy demand is dominating. The thermal simulations conducted estimated that the current thin-film technology could reduce a room's cooling load by 31% and that future photovoltaic technologies could possibly enable a façade to supply the air-conditioning load entirely and possibly even provide surplus energy for other uses.

Radhi [17] performed an energy simulation of façade-integrated photovoltaic systems applied to a commercial building in the United Arab Emirates. He found that the interaction between photovoltaic modules and the thermal performance of buildings in addition to the photovoltaic output made a significant difference. He also observed that the reduction in the building's total operational energy consumption was in the range of 1.1–2.2% and this was largely due to the reduction in heat gain and cooling load.

An experimental study using a test chamber in Hong Kong undertaken by Chow et al. [12] evaluated the energy performance of four different configurations of photovoltaic glazing systems: single glazing, double glazing, natural ventilating and force-ventilating, with single absorptive glazing being used as the standard benchmark. The results showed that photovoltaic glazing with 10% transmittance can effectively reduce direct solar transmission and excessive glare. On air-conditioning demands, the reduction in power consumption was 26% and 82% for single-pane and forced-ventilation cases, respectively.

In another study conducted in Hong Kong, Fung and Yang [18] investigated the semi-transparent BIPV's thermal performance. Semi-transparent photovoltaic modules which maintain transparent gaps between opaque solar cells were studied and they introduced and verified a model to predict the thermal performance of such glazing through a calorimeter box. Using a parametric analysis the solar cell coverage ratio, efficiency and module thickness were studied. They found that solar heat gain is a major component of the total heat gain, which was significantly affected by the area of the opaque solar cell.

However, there is still a lack of research on multi-functional performance of semi-transparent BIPV facades as well as its performance as compared with conventional glazing in tropical regions, where it is hot and humid whole-year round resulting in buildings being cooling-load dominated. In addition, many of the previous studies utilized theoretical modelling for the semi-transparent BIPV modules which might not truly reflect the ones currently available in the market. Published performance data reported by manufacturers are normally established under laboratory conditions which may not represent actual conditions prevalent in tropical locations, leading to substantially different in-use performance from the predicted. In this study, the overall energy performance of six commercially available semi-transparent PV

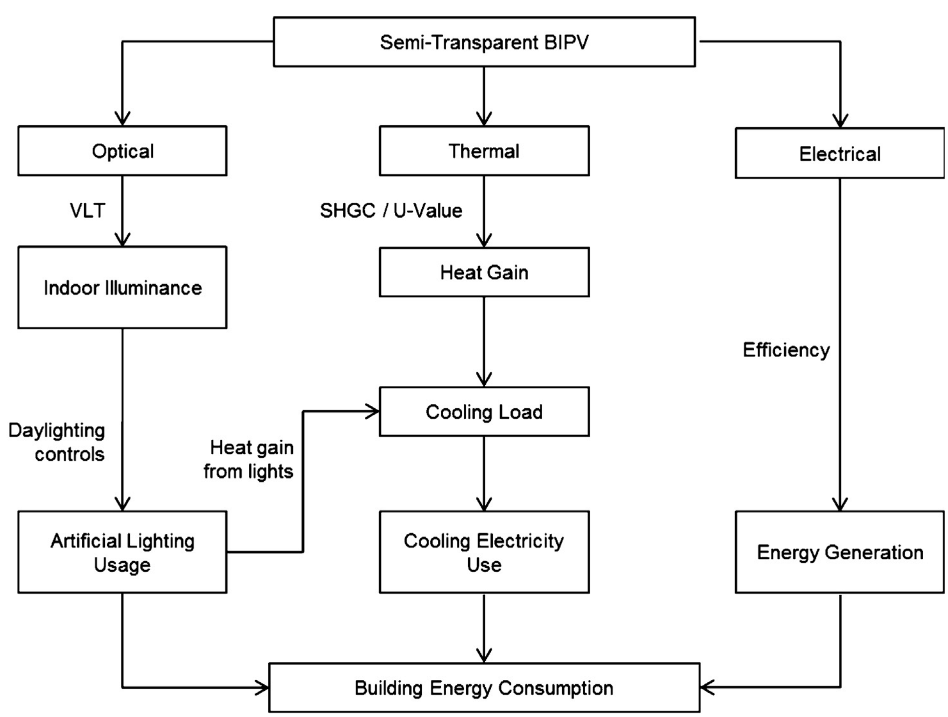

Fig. 1. Effects of semi-transparent BIPV application on tropical buildings' energy consumption.

modules was evaluated over different WWRs and across the four main orientations in Singapore, through the consideration of increase/reduction in cooling loads, daylight utilization and production of electricity. The objective of this paper is to present the findings of that study. Section 2 introduces a multi-functional index to quantify the total electricity savings, while the semi-transparent BIPV modules and simulation methodology are explained in Sections 3 and 4, respectively. Section 5 discusses the main results of this study with conclusions and highlights summarized in Section 6.

2. Holistic multi-functional index – Net Electrical Benefit (NEB)

Due to the multifunctional role that semi-transparent BIPV adopts, there are several parameters that can affect and define its energy performance. Therefore, BIPV's investigation with respect to energy-related impacts will require a new performance index, aimed at producing a holistic view. To optimize and analyze the design for BIPV, the effects of power generation and building physical aspects have to be evaluated. The multifunctional role will need to include both the positive and negative elements for a complete assessment of BIPV windows. Positive elements, when compared to an opaque wall with 0% WWR, are the PV electricity generation and electricity savings due to natural sunlight while the additional increase in cooling electricity is the negative element.

To objectively assess these three factors of electricity, the Net Electricity Benefit (NEB) is derived. As shown in Eq. (1), it is the sum of the lighting electricity savings and photovoltaic electricity production minus the increase/decrease in electricity consumption required for space conditioning (heating/cooling) as compared to a building with 0% WWR. When NEB is positive, the application of the semi-transparent BIPV windows would be justified as the energy savings, from day light use and generation, are higher than the increase in energy consumption for space conditioning. In this manner, NEB is a simple index capable of assessing the overall electricity benefit of incorporating a semi-transparent BIPV window, knowing that there is no other primary energy need in the tropics.

$$\mathrm{NEB} = L_{\text{savings}} - C_{\text{electricity}} + \mathrm{PV}_{\text{generation}} \quad [\mathrm{kWh/m^2}] \tag{1}$$

where, L_{savings} is the artificial lighting savings through the utilization of natural sunlight; $C_{\text{electricity}}$ is the increase in electricity consumption required for space conditioning due to transmission of additional solar heat gain; $\mathrm{PV}_{\text{generation}}$ is the photovoltaic window electricity generation output; and, m^2 is the unit gross floor area.

3. Semi-transparent BIPV modules in Singapore buildings

Due mainly to rapid urbanization, the number of high-rise buildings would be increasing and could possibly be the widest application for photovoltaic technology in the future. In this study, the integration of six commercially available semi-transparent BIPV modules was analyzed through computer simulations in terms of energy performance of office buildings in Singapore. Thin-film modules were selected due to their homogeneity in transmitting natural daylight. The six selected semi-transparent BIPV modules included two double glazed units and all were made of thin-film solar cell technologies; namely amorphous silicon and "micromorph" silicon, a tandem structure with an additional microcrystalline absorber underneath the amorphous layer.

As a first step, the modules were laboratory tested in order to determine a variety of relevant optical, thermal and electrical properties which are essential parameters for building energy simulations. This was performed as some of the information was not

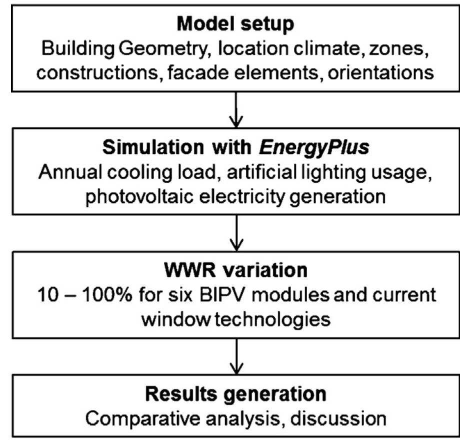

Fig. 2. Overview of research and simulation methodology.

readily available from the manufacturer's data sheet. The measurements took place in certified laboratories and the testing procedures along with the results are published elsewhere [19,20]. For the ease of reading, the module description, specifications and properties are compiled and shown in Table 1.

4. Performance simulation

A model of a typical office building, with a square floor plan with facades facing the four main orientations, was set up within *EnergyPlus* simulation software (version 7.0) with the definition of the building geometry, location, internal loads, façade properties and orientation. *EnergyPlus* is a building energy simulation software developed by the United States Department of Energy [21] which includes various program modules that enable simulating cooling/heating loads, daylighting and photovoltaic systems with repeated accurate results which had been validated through analytical, comparative and empirical tests [22,23]. An illustration of the research methodology for this paper is shown in Fig. 2.

A standard floor (L-30 m × B-30 m × H-3 m) was modelled to reduce computational loads. The space was divided into five zones, consisting of four perimeter zones (200 m^2 each), facing east, west, north and south and a core zone. The zones were separated by internal walls which were deemed adiabatic to prevent heat transfer in between so that each perimeter zone can be analyzed accurately. The core zone was not considered during the simulations. The window aspect ratio was maintained at 1:10 for all WWRs, similar to the length-to-height ratio of the external walls. A central cooling system with a COP of 3.37 was chosen for the building to comply with the building legislation requirements in Singapore [24,25]. The COP was used to determine the electricity consumption of the cooling system from the cooling loads obtained. Properties of the six semi-transparent BIPV were included in the model to be used for the windows. *EnergyPlus* weather-data file for Singapore was adopted for the location and climate which is a typical meteorological year (TMY) data commonly used with building energy performance software [26]. The plan view of the office is shown in Fig. 3, while the building description, construction details and internal heat gains are shown in Tables 2–4, respectively.

The model established was used to evaluate the impact on the energy consumption through the application of semi-transparent BIPV windows resulting from artificial lighting usage, space conditioning (cooling) energy usage and photovoltaic energy generation. Two analyses were conducted:

1. Parametric analyses on the WWR and orientations for six semi-transparent BIPV modules to investigate their effect on the

Table 1
Technical data and specifications of six semi-transparent BIPV modules under investigation.

	Module 1	Module 2	Module 3	Module 4	Module 5	Module 6
Module area (mm × mm)	980 × 950	1300 × 1100	1300 × 1100	1300 × 1100	989 × 930	980 × 950
Efficiency [%]	8.02	5.90	3.32	4.43	5.01	4.75
SHGC (measured)	0.289	0.413	0.298	0.387	0.154	0.123
U-value (measured) [W/(m^2 K)]	5.08	4.80	5.08	5.10	1.67	2.14
Visible light transmittance [%]	9.17	5.19	1.84	4.17	6.91	7.34
Photovoltaic technology	a-Si	μc-Si	μc-Si	μc-Si	a-Si	a-Si
Construction assembly	Glass–glass single pane laminate	Glass–glass single pane laminate	Glass–glass single pane laminate	Glass–glass single pane laminate	Double glazed unit	Double glazed unit
Appearance	Standard	Red	Golden	Dark blue	Standard	Standard

Note: a-Si, amorphous silicon; μc-Si, micromorph silicon.

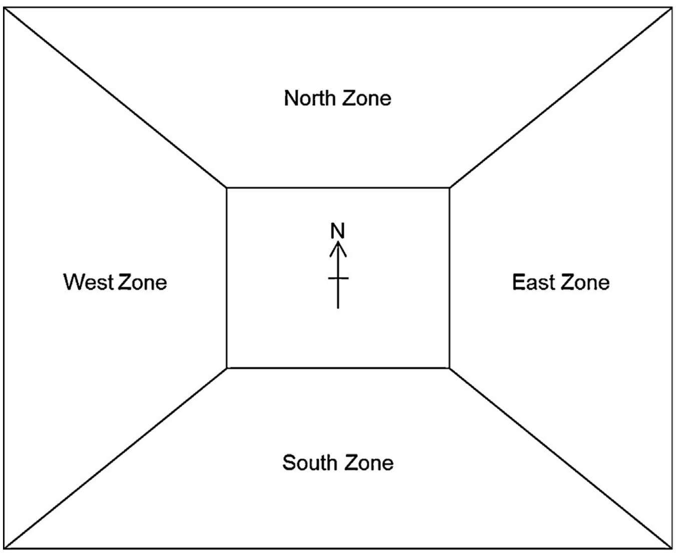

Fig. 3. Plan view of the simulated office building.

overall performance of the building based on their NEB (in kilowatts-hours per unit floor area per annum). The WWR was varied from 10% to 100% for the four main orientations (east, west, north and south).

2. Comparative analyses to explore the performance of semi-transparent BIPVs against four conventional window glazing systems (single glazing, double glazing, low-e glazing and tinted low-e glazing), in terms of total electricity consumption. This comparison was limited to buildings with highly glazed facades, and therefore only WWRs of 70–100% were considered. The properties of common window glazing types which were used for the comparison are shown in Table 5.

Table 2
Description of office building model for *EnergyPlus* simulations.

Parameters	
Total simulated area	800 m^2
Floor-to-ceiling height	3.0 m
Window aspect ratio (height:length)	1:10
Window-to-wall ratio (WWR)	10–100%
Illuminance setpoint	500 lux
HVAC temperature setpoint	22 °C
Occupancy	0.2 person/m^2
Lighting	10 W/m^2
Equipment	8 W/m^2
Infiltration rate	0.1 air changes per hour
Ventilation rate	3.0 m^3/(s m^2)
Operational hours	0900–1800 h (weekdays only)
BOS efficiency	0.90

Table 3
Construction details of office building model for *EnergyPlus* simulations.

Layers (outer to inner)	Thermal conductivity [W/(m K)]	Density [kg/m^3]	Specific heat [J/(kg K)]
Exterior wall			
200 mm heavyweight concrete	1.95	2240	900
50 mm insulation board	0.03	43	1210
Air space	(Thermal resistance = 0.15 m^2 K/W)		
19 mm gypsum board	0.16	800	1090
Ground floor			
200 mm heavyweight concrete	1.95	2240	900
Roof			
100 mm heavyweight concrete	0.53	1280	840
Air space	(Thermal resistance = 0.15 m^2 K/W)		
Acoustic tile	0.06	368	590

Table 4
Hourly variations of internal heat gains of office building model for *EnergyPlus* simulations.

	Occupants [%]	Lighting [%]	Electric equipment [%]
0–8 h	0	0	0
8–9 h	0	30	40
9–10 h	90	90	90
10–12 h	95	90	90
12–13 h	50	90	80
13–17 h	95	90	90
17–18 h	30	50	50
18–24 h	0	0	0

Table 5
Properties of traditional and current window glazing types.

Layers (outer to inner)	Solar transmittance	Visible transmittance	Thermal conductivity [W/(m K)]
Single glazing			
6 mm clear glass	0.775	0.881	0.9
Double glazing			
12 mm clear glass	0.653	0.841	0.9
6 mm air gap	–	–	–
6 mm clear glass	0.775	0.881	0.9
Double low-e glazing			
6 mm low-e glass	0.60	0.84	0.9
6 mm air gap	–	–	–
6 mm clear glass	0.775	0.881	0.9
Double low-e tinted glazing			
6 mm low-e tinted glass	0.36	0.5	0.9
6 mm air gap	–	–	–
6 mm clear glass	0.775	0.881	0.9

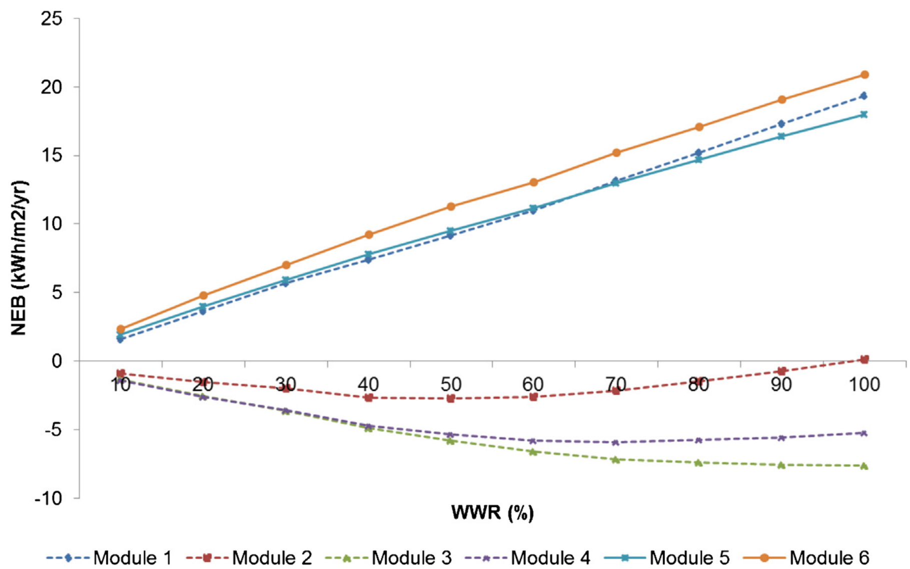

Fig. 4. Effects of WWR on NEB for various modules on east façade orientation.

The results of these analyses are discussed next.

5. Results and discussion

5.1. Parametric analyses on window-to-wall ratio and orientations

Figs. 4–7 show the overall annual NEB as a function of WWR for the six semi-transparent BIPV modules for east, west, north and south orientations, respectively. Modules 1, 5 and 6 portrait very similar performances with their NEBs being positive throughout all WWR and across all four orientations. Their NEBs vary from 1.51 to 20.84 kWh/(m^2 yr) and increase steadily with the WWR. Performances of modules 2, 3 and 4, however, are very much different. As the WWR increases, their NEBs decrease before increasing slowly after 60% WWR. Out of these 3 modules, only module 2 manages to obtain positive NEB which is only achieved at high WWRs (70–100%). Module 2's NEB range from −2.72 to 2.26 kWh/(m^2 yr), while for modules 3 and 4 they are at −7.59 to −0.98 kWh/(m^2 yr) and −5.88 to −0.96 kWh/(m^2 yr), respectively.

The results indicate that the NEBs of BIPV can be very different and dependent on the WWR adopted. Double-glazed BIPVs (modules 5 and 6) show good performance due to their better thermal performance, even though they have slightly lower photovoltaic efficiencies. Good thermal performance for facades is important for tropical areas like Singapore which have high outdoor temperature and solar heat gain. Single-glazed BIPVs (modules 1–4) have higher *U*-values and SHGCs which allow heat gain and results in higher cooling energy loads. However, module 1 with similar performance to the double-glazed window indicates that higher photovoltaic efficiency and/or VLT can offset the increase in thermal gains. To further understand the impacts of the individual positive elements (reduction in artificial lighting and PV electricity generation), their percentages are tabulated from the simulation results and shown in Table 6. It can be seen that PV electricity generation is the main positive component for NEB ranging from 66.9% to 87.4% for all modules across various orientations. For this reason, module 1

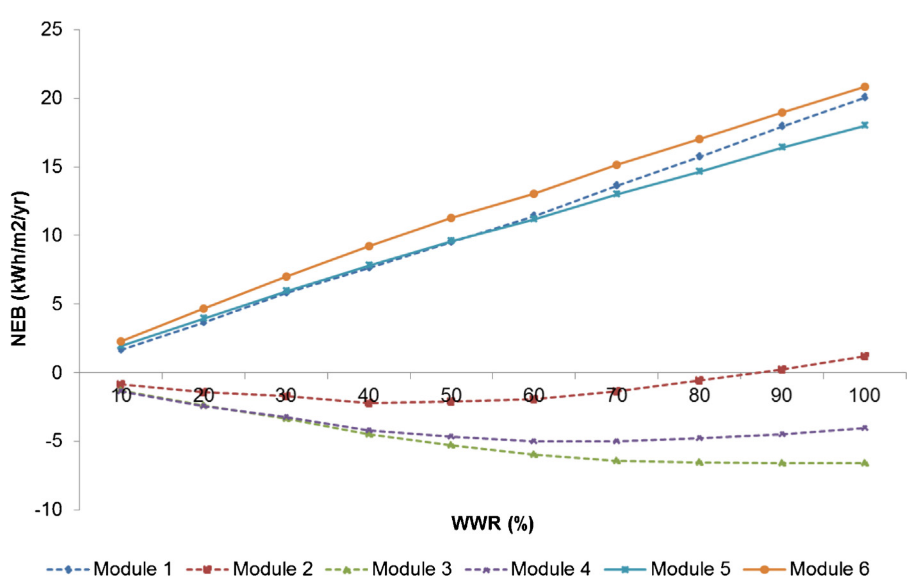

Fig. 5. Effects of WWR on NEB for various modules on west façade orientation.

Table 6
Breakdown of positive impacts of semi-transparent BIPV modules on two critical parameters: artificial lighting and PV electricity generation.

	Reduction in artificial lighting electricity component [%]		PV electricity generation component [%]	
	Minimum	Maximum	Minimum	Maximum
Single-glazed BIPV				
Module 1	21.7	27.6	72.4	78.3
Module 2	18.7	22.6	77.4	81.3
Module 3	12.6	15.6	84.4	87.4
Module 4	19.7	23.9	76.1	80.3
Double-glazed BIPV				
Module 5	25.2	30.6	69.4	74.8
Module 6	27.4	33.1	66.9	72.6

can outperform all other single-glazed BIPVs as its photovoltaic efficiency is the highest.

The results also suggest that, in Singapore it is possible to integrate semi-transparent BIPV modules on facades that do not face the sun path. As seen from Figs. 6 and 7, the modules 1, 5 and 6 generate positive NEBs for all WWRs on north/south orientations where diffuse sunlight contributes approximately 70% of skylight received [27]. Module 2 is also able to achieve positive NEB when the WWR is 60% or more. Furthermore, diffuse sunlight is known to be 'cooler' than direct sunlight which reduces the solar heat gain in the zones and in turn, decreases the amount of cooling required and also the initial sizing of the air-conditioning system. This finding strongly supports extensive semi-transparent BIPV adoption across all orientations in tropical Singapore's high-rise buildings.

5.2. Comparison with common window glazing

The total annual electricity consumption of ten window types (six semi-transparent BIPV modules and four conventional glazing systems) for highly glazed facades (WWR of 70% or more) is compared and shown in Fig. 8. The four commonly used window glazing types portray a consistent increase of approximately 3.0 kWh/(m^2 yr) for every 10% increase in WWR. In contrast to that,

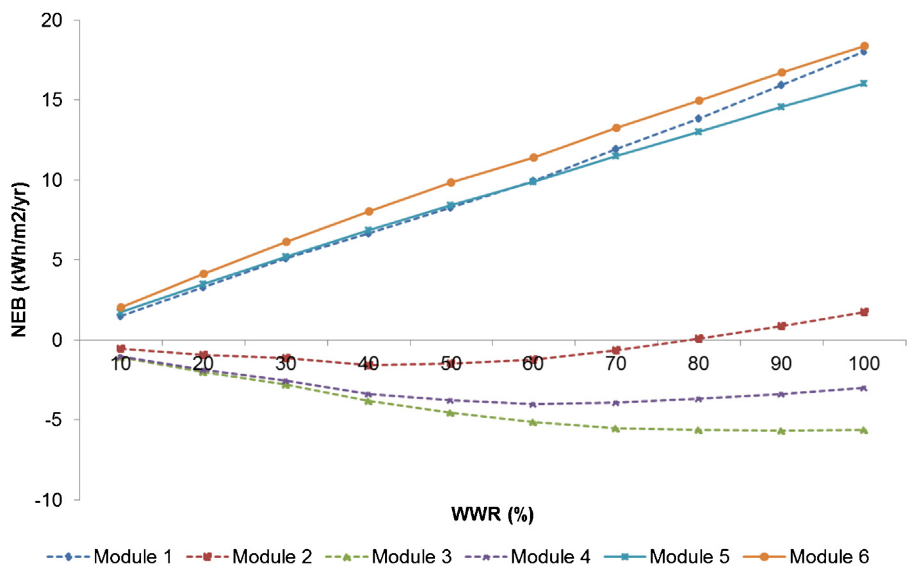

Fig. 6. Effects of WWR on NEB for various modules on north façade orientation.

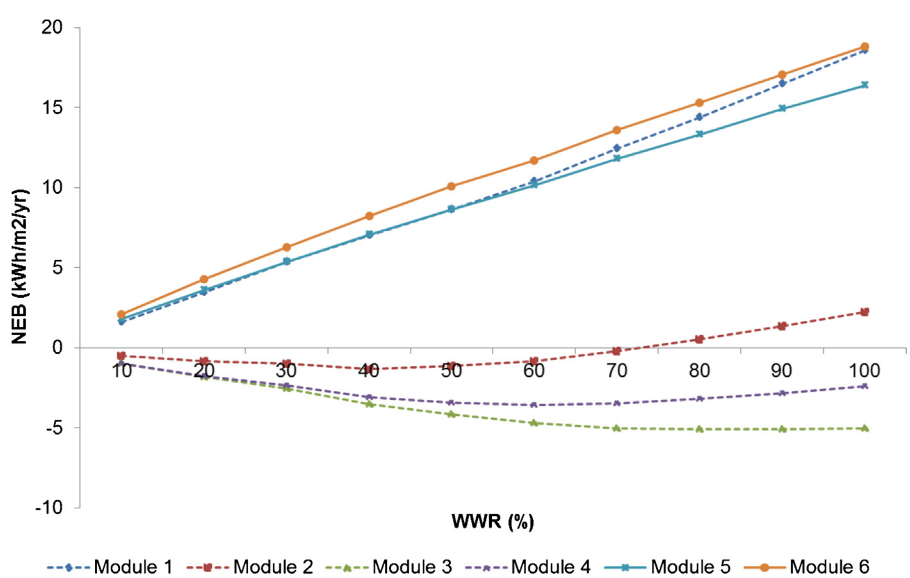

Fig. 7. Effects of WWR on NEB for various modules on south façade orientation.

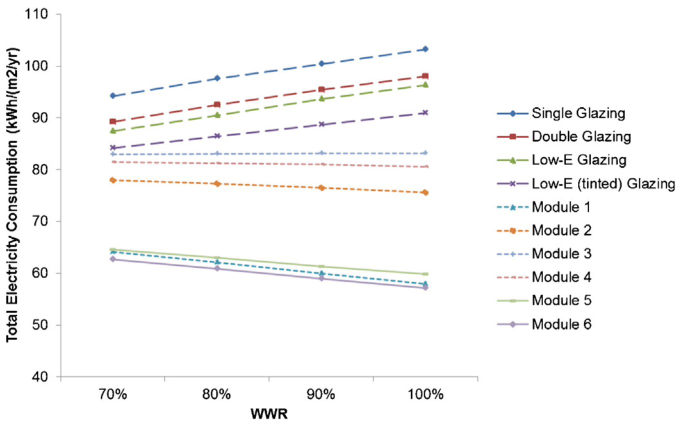

Fig. 8. Annual total electricity consumption of lighting, air-conditioning with consideration of PV generation for all ten window types (six semi-transparent BIPV modules and four conventional glazing systems).

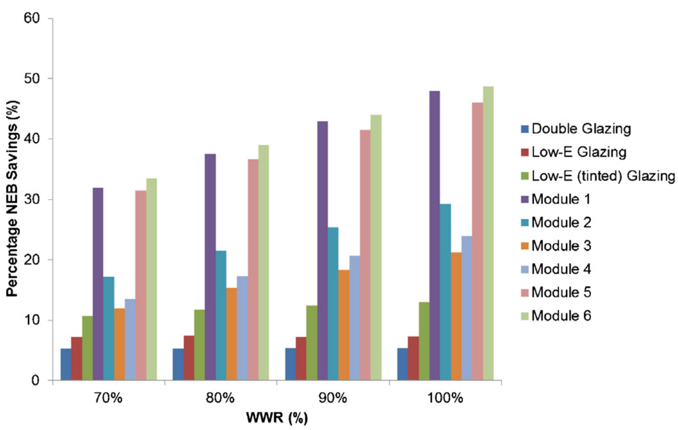

Fig. 9. Percentage of total NEB savings through alternative window types with single glazing as reference (therefore not shown here).

all the semi-transparent BIPV modules show a decreasing trend of 0.15–2.14 kWh/(m^2 yr).

The potential savings that may be achieved by adopting semi-transparent BIPV and other alternative window types as compared with currently used single-glazing system are shown in Fig. 9. It can be seen that the semi-transparent BIPV modules can achieve significantly higher percentage savings with increasing WWR as compared to current glazing types. The double-glazed, low-e and tinted low-e glazing exhibit consistent savings of approximately 5.4%, 7.3% and 12.0%, respectively. The semi-transparent BIPV modules, however, indicate a consistent increase in savings rate of between 16.7% and 41.3% at WWR range of 70–100%. Although the double-glazed BIPV units show the largest percentage savings, the results also indicate that even the lower performing semi-transparent BIPVs with negative NEBs are relatively more energy efficient compared with common window technologies.

6. Conclusion

This research has demonstrated the energy saving potential of semi-transparent BIPV windows in highly glazed buildings. Although the performances of the six modules were different, they all out-performed current window types commonly available in the market.

The study revealed that,

- Singapore's highly diffuse skylight conditions means semi-transparent BIPV can be adopted even on orientations that do not receive direct solar gains.
- PV efficiencies and good thermal properties are essential to achieve better NEB performance.
- BIPV units outperform all other commonly used glazing systems when integrated in highly glazed buildings.

It also has to be noted that the investigated semi-transparent BIPV modules have VLT of less than 10%. When replacing conventional windows, the external view might be limited or blurred. Although the interiors are supplemented by artificial lighting, this can prevent some building developers or architects from adopting semi-transparent BIPVs when making the final design decision. Nonetheless, this study indicated the potential of semi-transparent BIPV replacing glazed facades within its defined scope.

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